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Soil Water Evaporation in Irrigated Corn

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ABSTRACT. *Three simulation models were evaluated for their ability to predict bare soil water evaporation in irrigated corn. The models were Ritchie, CERES-Maize, and EPIC. Soil water evaporation field data, collected in North Platte, Nebraska, were used to evaluate the models. Small lysimeters under the crop canopy measured soil water evaporation during the growing season. Mini-lysimeters excluded root growth, but soil water contents were adjusted to surrounding soil weekly. Micro-lysimeters were installed on a daily basis, which allowed for soil water extraction until the day of data collection. Soil water evaporation simulated by Ritchie and CERES-Maize models most closely matched evaporation measured by North Platte lysimeter data. EPIC predicted lower soil water evaporation rates during complete canopy cover.* ***Keywords.*** *Evapotranspiration, Transpiration, Soil evaporation, Model evaluation.*

Soil water evaporation and transpiration from plants are important components in building and understanding soil water balances (Klocke et al., 1985). Irrigators and dryland farmers are interested in reducing evaporation directly from the soil surface, especially if water supplies are limited (Schneekloth et al., 1991). Reduced soil water evaporation may lead to more water available for transpiration. Grain yields, especially in water short areas, will benefit from reduced soil water evaporation and increased water use efficiency.

Soil water evaporation and transpiration are also important for computer simulations of soil water balances. Soil water uptake by plants influences the distribution of water and nutrients in the root zone. Evaporation from the soil surface influences soil water infiltration and distribution, especially near the surface. Crop simulations to study improved management practices for more efficient water use and for reduced pollution potential need accurate predictions of evaporation.

Two crop simulation models currently used for water quality and water quantity studies are CERES-Maize (Jones and Kiniry, 1986) and EPIC (Sharpley and Williams, 1990). Soil water evaporation and transpiration are treated as separate processes. The CERES-Maize approach follows directly on the development by Ritchie (1972). Ritchie and CERES-Maize simulate transpiration as a function of leaf area index (LAI). Soil water evaporation is simulated as either a function of energy reaching the soil surface (energy limiting) or is limited by the soil's ability to move water to evaporating surfaces (soil limiting). Energy limited soil water evaporation is a function of LAI in Ritchie and CERES-MAIZE and a function of crop dry matter accumulation and surface cover in EPIC. Soil limited evaporation is a function of time in Ritchie and CERES-Maize and a function of soil water content in EPIC. Energy limited evaporation rates from bare soil exceed soil limited rates. Frequent wetting of the soil surface, as in irrigation management, causes more energy limited evaporation than in rain fed crops (Todd et al., 1991)

Villalobos and Fereres (1990) reported on a version of lysimeters for soil water evaporation measurements. Their lysimeters were 300 mm (12 in.) long and 200 mm (8 in.) in diameter with wall thickness of 2 mm (0.08 in.). Lysimeter walls and bottoms were constructed with perforated steel, which left 60% of the surface area open for root penetration. Lysimeters were filled by pressing perforated cylinders into undisturbed soil. Every lysimeter was placed in the field at the start of the growing season and only used for one day of measurement. Roots could grow into the lysimeters and extract water until the day before evaporation measurements were made. At that time the roots were cut around each lysimeter to prevent further water extraction by plants. The lysimeters were removed, sealed, weighed, and returned to the field. The following day the lysimeters were weighed prior to being discarded. Villalobos and Fereres found a relationship for energy limited soil water evaporation (EOS) as a function of evapotranspiration for a grass reference crop (EO) and LAI, EOS = EO EXP(−0.41 LAI).

Soil water evaporation was measured in irrigated corn in a field experiment (Todd et al., 1991) which was conducted independent of model development research. The objective of this study was to compare the field results with computer simulation models to predict soil water evaporation in irrigated corn.

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Model Descriptions

The Ritchie model was the most "calibrated" model for the North Platte site. CERES-Maize and EPIC models were "off the shelf" versions.

Ritchie

The model, developed by Ritchie (1972), uses the concept of two-stage soil water evaporation. When the surface is wet, water evaporates at a potential rate limited only by energy available at the surface. Rosenthal et al. (1977) used Ritchie's model for irrigated corn in Kansas. They slightly modified Ritchie's empirical relationships for potential soil evaporation, and we used these modifications in our study. The combination of Ritchie's and Rosenthal's work led to potential or energy limited rates of soil water evaporation (EOS) predicted by:

$$EOS = EO\,(1 - 0.43\,LAI) \quad \text{for } LAI < 1 \tag{1}$$

$$EOS = EO\,EXP\,(-0.389\,LAI + 0.1438) \quad \text{for } LAI > 1 \tag{2}$$

As soils dry, evaporation rates become limited by unsaturated hydraulic conductivity which is strongly influenced by water content and texture. Soil limited evaporation (ES) in the Ritchie model was:

$$ES = C\,T^{1/2} \tag{3}$$

where C is an empirical constant depending on soil texture and T is time from the start of soil limited evaporation. With this approach it is important to determine when energy limited evaporation stops and soil limited evaporation starts. Ritchie used a threshold value, U, for accumulation of energy limited evaporation before soil limited evaporation starts. U depends on soil texture. Ritchie also developed logic to determine if a precipitation event would shift evaporation rates from soil limiting back to energy limiting. This was particularly important for small precipitation events.

Based on field studies, Ritchie developed an empirical relationship to calculate transpiration (EP). Transpiration is calculated independently from soil evaporation in the model:

$$EP = EO\,[-0.21 + 0.70\,(LAI)^{1/2}]$$

$$\text{for } 0.1 < LAI < 3.0 \tag{4}$$

When LAI exceeds 3.0, transpiration equals potential evapotranspiration. However, if the summation of ES or EOS and EP exceeds EO, EP is reduced so that EP plus ES or EOS equals EO.

CERES-Maize

The approach to soil water evaporation predictions in CERES-Maize (Jones and Kiniry, 1986) comes directly from Ritchie (1972). They did the modify function for potential evaporation at the soil surface:

$$EOS = EO\,(1 - 0.43\,LAI) \quad \text{for } LAI < 1$$

$$EOS = EO/[1.1\,EXP(-0.4\,LAI)] \quad \text{for } LAI > 1 \tag{5}$$

For soil limited evaporation, the value for C in equation 3 is held constant at 3.5 mm $d^{-1/2}$ (0.14 in. $d^{-1/2}$) and the user chooses a value for U. Suggested values for U ranged from 6 mm (0.24 in.) for sands and shrinking clays to 9 mm (0.35 in.) for loams and 12 mm (0.47 in.) for clay loams.

CERES-Maize follows the Ritchie logic for predicting transpiration:

$$EP = EO\,[1.0 - EXP(-LAI)] \quad \text{for } LAI < 3 \tag{6}$$

Again, transpiration is predicted to equal EO for LAI greater than 3, but it is reduced if soil water evaporation is occurring.

EPIC

Soil water evaporation is predicted with a two-stage approach by the EPIC model (Sharpley and Williams, 1990). Potential soil water evaporation (EOS) is calculated by:

$$EOS = EO\,(EA) \tag{7}$$

where EA is a surface cover index that is a function of the sum of above ground biomass and crop residue (CV in t/ha) according to:

$$EA = EXP(-0.1\,CV) \tag{8}$$

Potential soil water evaporation depends on EO and the amount of soil surface shading.

Water content in the top 0.2 m (7.9 in.) layer of soil reduces the calculated potential evaporation rate as the soil dries from field capacity to wilting point. For a soil layer that limits soil water evaporation, the following relationship holds:

$$ES = EOS\,EXP[(2.5(SW - FC)/(FC - WP)]$$

$$\text{for } SW < FC \tag{9}$$

where SW (mm) is the soil water content in the top 0.2 m (8 in.), FC (mm) is soil water content at field capacity in the top 0.2 m (8 in.), and WP (mm) is soil water content at wilting point in the top 0.2 m (8 in.).

Transpiration is calculated by:

$$EP = (EO\,LAI)/3.0 \quad \text{for } LAI < 3 \tag{10}$$

$$EP = EO \quad \text{for } LAI > 3 \tag{11}$$

Equation 11 forces ES to zero when LAI exceeds 3. Recently EPIC developers have added logic to reduce EP so that EP and ES will total EO (Williams, personal communication, 1994). This logic corresponds to the approach used in Ritchie and CERES-Maize and was used in the version of EPIC that we evaluated.

Field Procedures

The experimental site was at University of Nebraska's West Central Research and Extension Center near North Platte, Nebraska. Soil was Cozad silt loam (Fluventic

Haplustoll) with available water capacity of 0.17 m^3 m^{-3}. The semi-arid climate has a mean annual precipitation of 480 mm (19 in.).

Mini-lysimeters, described by Todd et al. (1991), measured soil water evaporation during 1986 and 1987. The mini-lysimeters were constructed from PVC irrigation pipe and were 225 mm (9 in.) deep with an inside diameter of 150 mm (6 in.) and wall thickness of 3.2 mm (0.13 in.). PVC pipe sections were filled by pressing them into the soil with a hydraulic soil sampler. Mini-lysimeters were then excavated and sheet metal disks were sealed to the bottom to retain soil. Mini-lysimeters were placed in the field in holes lined with open-ended sheet metal cylinders which served as soil retaining walls. Four replications of lysimeters were weighed daily. Days with irrigation or rain were not used. Since mini-lysimeters did not have water extracted by roots, average soil water content in the mini-lysimeters was adjusted to the surrounding field soil after each irrigation and after rainfall events totalling more than 20 mm. Soil water content was measured in the surrounding field following irrigation or rainfall and enough water was added to the mini-lysimeters to match field conditions.

Micro-lysimeters were also used during 1987. They were constructed on a daily basis with a soil core sampler. Aluminum retaining cylinders [75 mm (3 in.) I.D. × 75 mm (3 in.) long] were manually pressed into undisturbed soil. Six replications of filled cylinders were each placed in a can, weighed, and returned to the field. Micro-lysimeters were reweighed 24 h later and then discarded. Soil water was normally extracted by roots until the day that evaporation was measured. The micro-lysimeters were smaller and took more time to install than the mini-lysimeters. They were intended to overcome the problem of no root extraction in the mini-lysimeters.

Model Evaluation Procedures

Potential evapotranspiration for a grass reference was calculated from weather data at the North Platte site using the Penman-Monteith equations from the EPIC model. These values for EO were then used as inputs to the Ritchie, CERES-Maize, and EPIC models. Daily soil water evaporation data from North Platte were divided by the same day's EO values to derive normalized ES.

Leaf area index measurements from the North Platte field plots were used as inputs to the Ritchie and CERES-Maize calculations of evaporation. LAI values simulated by EPIC were used for EPIC transpiration calculations.

Soil parameters C and U for the Ritchie model were determined from laboratory soil column experiments described by Klocke et al. (1985). C and U were 6.1 mm $d^{-1/2}$ (0.24 in. $d^{-1/2}$) and 10.2 mm (0.4 in.), respectively. The same value for U was used as input to the CERES-Maize calculations, but the standard value for C of 3.5 mm $d^{-1/2}$ (0.14 in. $d^{-1/2}$) was used.

Results

Growing Season Comparisons

Growing season EO and ES totals simulated from Ritchie, CERES-Maize, and EPIC for the North Platte site are presented in table 1. There is close agreement between Ritchie and CERES-Maize because the only difference was the calculation of soil limited evaporation. EPIC differed from the other models because soil limited evaporation was calculated differently, which will be discussed in following sections. Also, EPIC may have predicted somewhat less soil water evaporation in 1986 because measured LAI in the field actually peaked at 5 instead of the EPIC-predicted value of 6 (fig. 1). The crop did follow predicted development in 1987.

Since data were not available from mini-lysimeters during days of rainfall and irrigation, comparisons were limited to 78 and 72 days for 1986 and 1987, respectively. For those days when mini-lysimeter data were available, soil water evaporation totals are in table 2 and normalized results are in table 3. The cumulative results from the two years were very consistent. Soil water evaporation predicted by Ritchie and CERES-Maize models was within 15% of measured evaporation. However, soil water evaporation predicted by EPIC was 43% less than measured.

Table 1. Growing season potential evapotranspiration (EO) and soil water evaporation (ES) for Ritchie, CERES-Maize, and EPIC models (North Platte location)

	1986 (mm)	1987 (mm)	Mean (mm)
EO (Grass)	815	851	833
ES (Ritchie)	258	238	241
ES (CERES-Maize)	230	213	222
ES (EPIC)	158	136	147
Number of days	130	126	128

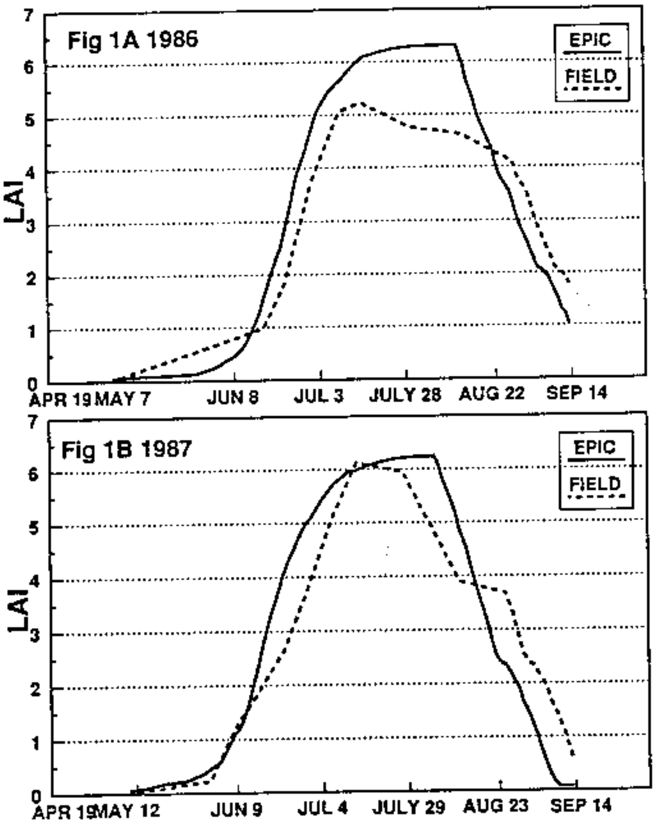

Figure 1–EPIC-calculated LAI and field measured LAI for 1986 and 1987.

Micro-lysimeter results were available for 52 days of the growing season at North Platte in 1987 (table 4). Micro-lysimeters had 12% less soil water evaporation than the mini-lysimeters and the same as predicted by the Ritchie and CERES-Maize models. The normalized soil water evaporation predictions from the EPIC model were consistently lower.

Daily Comparisons

Simulated daily soil water evaporation from the models was compared with the mini-lysimeter data (fig. 2). The Ritchie and CERES-Maize models somewhat under-predicted soil water evaporation measured by mini-lysimeters. Linear regressions with intercepts forced through the origin had slopes ranging from 0.76 to 0.89. The daily data varied from this regression, which was to be expected. The model predictions and measurements may have moved from energy limited evaporation through a transition to soil-limited evaporation at different times. Not having root extraction in the mini-lysimeters also may have contributed to variation between measured and simulated evaporation. EPIC underpredicted mini-lysimeter results, especially for the lower soil-limited evaporation rates. Since EPIC accounts for soil water extraction by roots, simulated soil limited evaporation may be predicted to occur more frequently than actually occurred in the mini-lysimeters. However, micro-lysimeters showed closer agreement with Ritchie and CERES-Maize (table 4).

Daily soil water evaporation predictions and measurements were normalized with potential ET for 1986 (fig. 3). Each of the models was compared with the mini-lysimeter data. The pattern of energy limited evaporation simulated by Ritchie and CERES-Maize is expressed as the inverted shape of the LAI curve. Energy-limited evaporation is more evident during the early part of the growing season when the crop was smaller and before irrigation started. Ritchie and CERES-Maize models also followed the trend of the mini-lysimeters late in the growing season when evaporation rates increased as LAI decreased. Evaporation predicted by EPIC tended to be less than the mini-lysimeters, especially after early July. Mini-lysimeters were mostly in energy-limited evaporation while EPIC-predicted, soil-limited evaporation at much lower rates. The influence of decreasing soil water content was evident in EPIC's predictions of evaporation. Since EPIC calculated energy-limited evaporation as a function of dry matter accumulation, late season evaporation stayed more

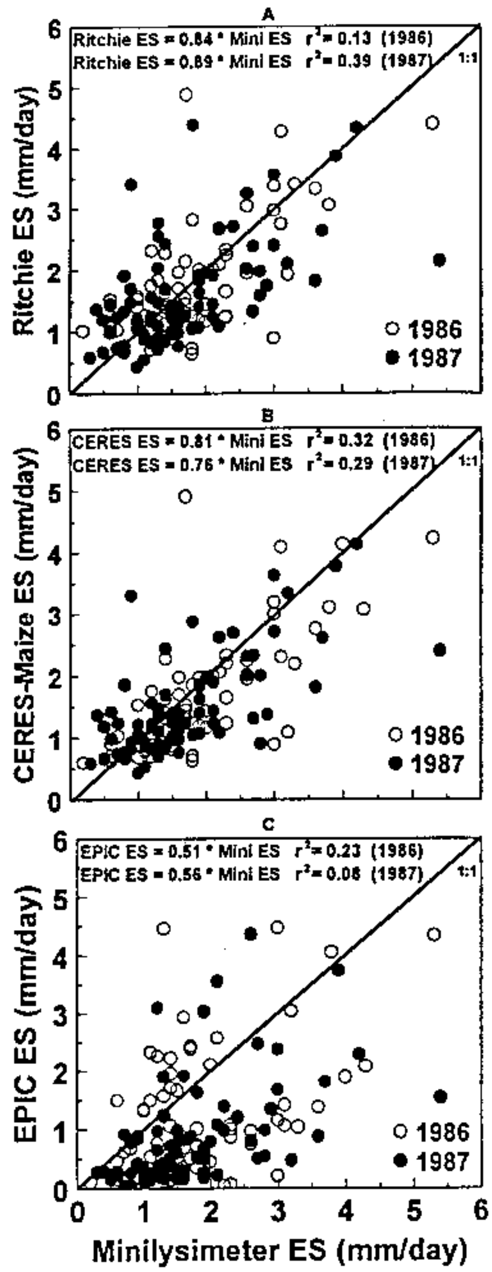

Figure 2–Soil water evaporation (ES) for Ritchie (a), CERES-Maize (b), and EPIC (c) models and mini-lysimeter ES.

Table 2. Potential evapotranspiration (EO) and soil water evaporation (ES) for days with mini-lysimeter data (North Platte location)

	1986 (mm)	1987 (mm)	Mean (mm)
EO (Grass)	536	514	525
ES (Ritchie)	126	131	129
ES (CERES-Maize)	118	113	116
ES (EPIC)	70	84	77
ES (mini-lysimeters)	134	136	135
Number of days	78	72	75

Table 3. Normalized soil water evaporation (ES/EO) for days with mini-lysimeter data (North Platte location)

	1986	1987	Mean
ES/EO (Ritchie)	0.23	0.25	0.24
ES/EO (CERES- Maize)	0.22	0.22	0.22
ES/EO (EPIC)	0.13	0.16	0.15
ES/EO (mini-lysimeters)	0.25	0.26	0.26

Table 4. Normalized soil water evaporation (ES/EO) for days with micro-lysimeter data (North Platte location)

	1987
ES/EO (Ritchie)	0.25
ES/EO (CERES-Maize)	0.23
ES/EO (EPIC)	0.12
ES/EO (mini-lysimeters)	0.27
ES/EO (micro-lysimeters)	0.24
Number of days	52

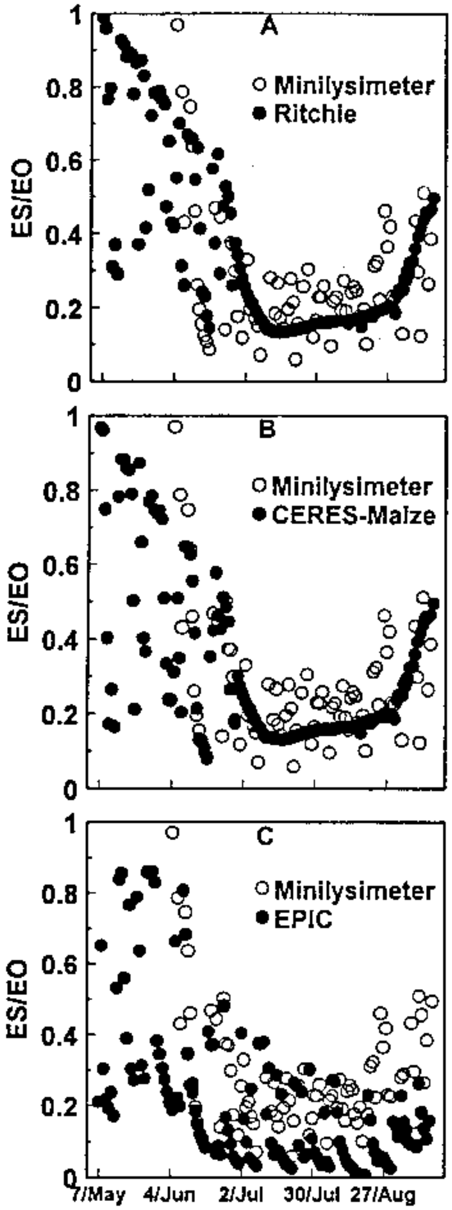

Figure 3–Normalized soil water evaporation (ES/EO) for Ritchie (a), CERES-Maize (b), and EPIC (c) models and mini-lysimeters for 1986.

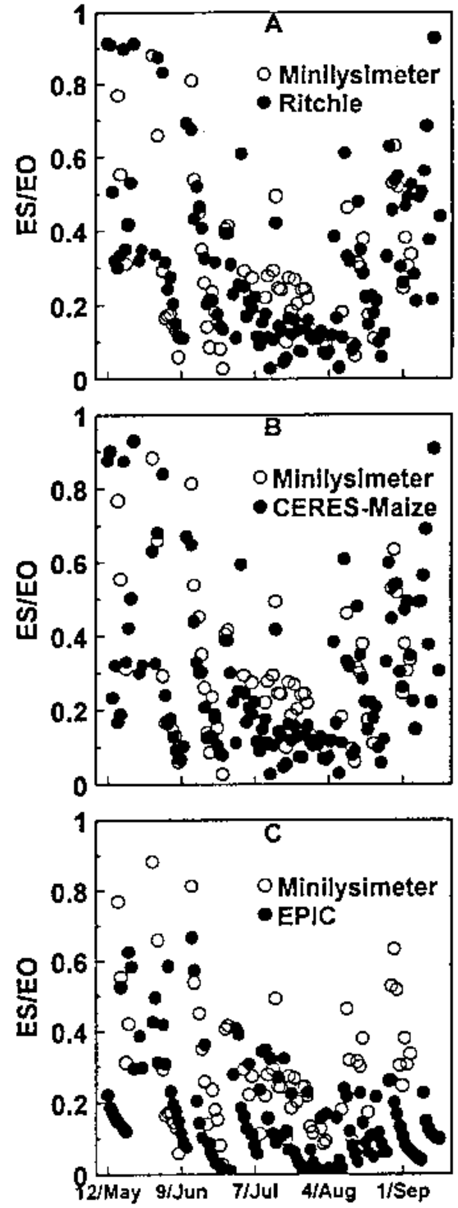

Figure 4–Normalized soil water evaporation (ES/EO) for Ritchie (a), CERES-Maize (b), and EPIC (c) models and mini-lysimeters for 1987.

constant compared to increasing soil water evaporation indicated by Ritchie and CERES-Maize.

Some of the same trends were found in 1987 (fig. 4). Apparently, more switching from energy to soil limited evaporation led to wider variations in day to day evaporation rates than were observed in 1986. EPIC still showed a strong tendency for soil limited evaporation throughout the growing season, with successive days of declining evaporation rates. Late season evaporation also increased as LAI decreased in the mini-lysimeters and the Ritchie and CERES-Maize simulations.

Energy-limited Evaporation

Energy-limited evaporation data and predictions were compared in figure 5. Ritchie and CERES-Maize are in close agreement. At peak LAI, EPIC tended to have higher evaporation rates than the other two models. Energy-limited evaporation was quite variable in the field. The

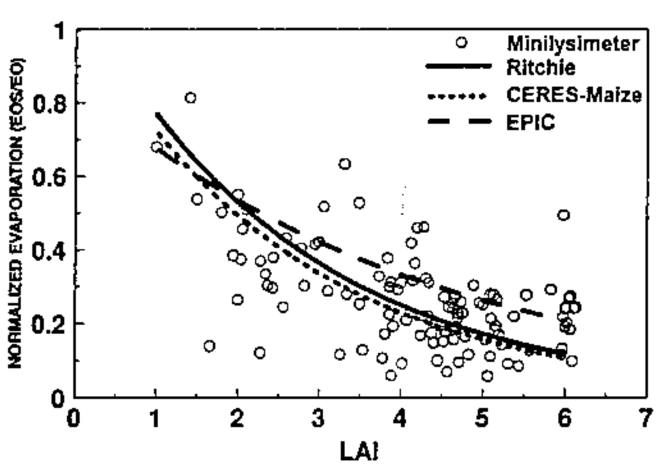

Figure 5–Normalized energy-limited soil water evaporation (EOS/EO) as a function of LAI.

Ritchie model was used to determine when evaporation switched from energy to soil limited. The transition may have occurred earlier than predicted in the field. Some of the lower evaporation measurements may have actually been soil limited. Since average soil water content in mini-lysimeters was matched with surrounding soil once each week during irrigation, energy-limited evaporation tended to follow trends from the models.

SUMMARY

The Ritchie model simulations of soil water evaporation, with calibration from Rosenthal et al., (1977) and laboratory-derived soil parameters, matched mini-lysimeter measurements from the field the closest. "Off the shelf" simulations with CERES-Maize also matched well with mini-lysimeter measurements. CERES-Maize had slightly less soil-limited evaporation than Ritchie predicted. EPIC simulated energy-limited evaporation similar to the other methods, except when LAI decreased toward the end of the growing season. The addition of logic to allow for soil water evaporation when LAI is more than 3.0 has improved EPIC's predictions. EPIC tended to shift from energy-limited to soil-limited evaporation sooner than the other methods during periods with maximum LAI. This gave lower evaporation rates and less evaporation overall. Lack of root extraction in mini-lysimeters may have caused more evaporation from wetter than normal soils. Results from micro-lysimeters, which were subject to root extraction until the day of evaporation measurements, suggested that mini-lysimeters overpredicted evaporation by 12%. Ritchie and CERES-Maize predictions were nearly identical to micro-lysimeter results.

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